Three Three-year aging of prototype flight laser at 10 kHz and 1 ns pulses with external frequency doubler for ICESat-2 Mission.

Paper 9834-7 in Laser Technology for Defense and Security XII, SPIE Defense + Commercial Sensing, Baltimore, Maryland, April 17-21, 2016.

Oleg A. Konoplev[*a], Furqan L. Chiragh[b], Aleksey A. Vasilyev[c], Ryan Edwards[e], Mark A. Stephen[d], Elisavet Troupaki[d], Anthony W. Yu[d], Michael A. Krainak[d], Nick Sawruk[e], Floyd Hovis[e], Charles F. Culpepper[e], Kathy Strickler[f].

[a]*Science Systems and Application Inc., 10210 Greenbelt Road, Suite 600, Lanham, MD, 20706*
[b]*Pinnacle Engineering & Management Solutions, 11779 Somerset Ave., Princess Anne, MD, 21853*
[c]*Trident Vantage Systems LLC.*
[d]*NASA Goddard Space Flight Center, Laser and Electro-Optics Branch, Greenbelt, MD 20771*
[e]*Fibertek Inc., 13065 Dulles Technology Dr., Herndon, VA 20171*
[f]*Alcyon Technical Services (JV)-LLC, Lanham MD*

[*]**Email:** oleg.a.konoplev@nasa.gov

Talk Outline

- Introduction & Motivation
- EDU-2 Laser Details
- Experimental Test Setup
- Details of External Life-Frequency Doubler Cell
- SHG, Optimization of Doubler Cell, Step-Stress 1&2
- Life-Aging Results
  - Timelines
  - Life-Aging Data @ 1064 nm
  - Life-Aging Data @ 532 nm
- LBO crystal surface changes
- Life-Time Prediction
- Conclusions

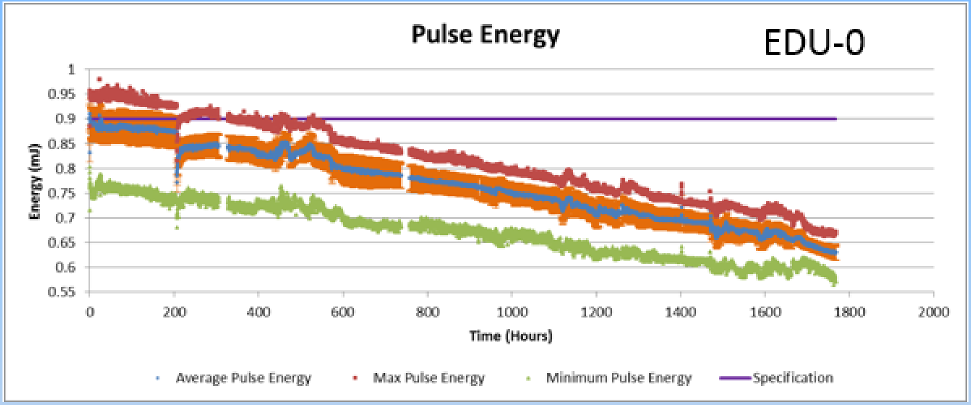
Motivation

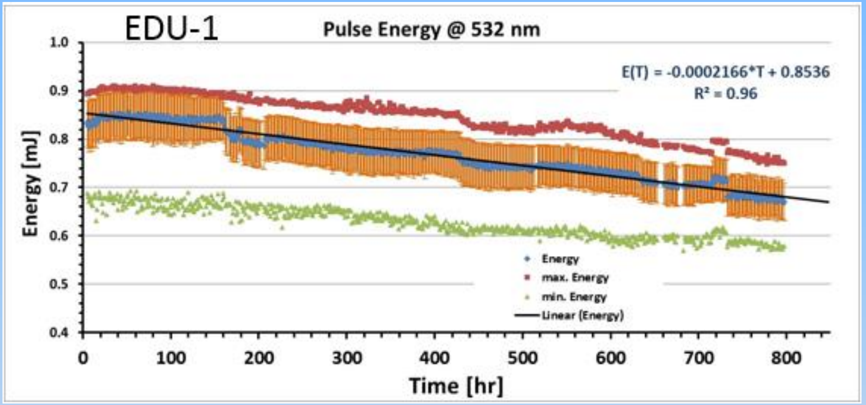
NASA's ICESat-II Mission; Laser Reliability Verification

- ATLAS is the name of the instrument on ICESAT-II
  - ATLAS instrument incorporate doubly redundant, High Rep-Rate, highly efficient Laser operating at 532 nm, 10 kHz, 1.5 ns, up to 9W:
- **1. Center wavelength 532.272 nm ±15pm, vacuum wavelength (BW≤~10pm)**
- **2. Wall-plug efficiency to 532 nm > 5% at laser case temperature 25°C**
- **3. Repetition rate 10 ±0.3 kHz**
- **4. Pulse energy adjustable within 250 uJ – 925 μJ (in 12 equal increments)**
- **5. Mean pulse width < 1.5 ns**
- **6. Polarization linear, contrast >100:1**
- **7. Spatial mode 1.6X diffraction limit (M^2< 1.6)**
- **8. Shot-to shot pointing stability < 11 μrad**
- **9. Boresight shift during vibration testing < 200 μrad**
- **10. Lifetime: 3 years + 60 days for each laser**

Motivation, continued

The first couple of Prototype Systems delivered to GSFC in 2011 exhibited excessive degradation at 532 nm



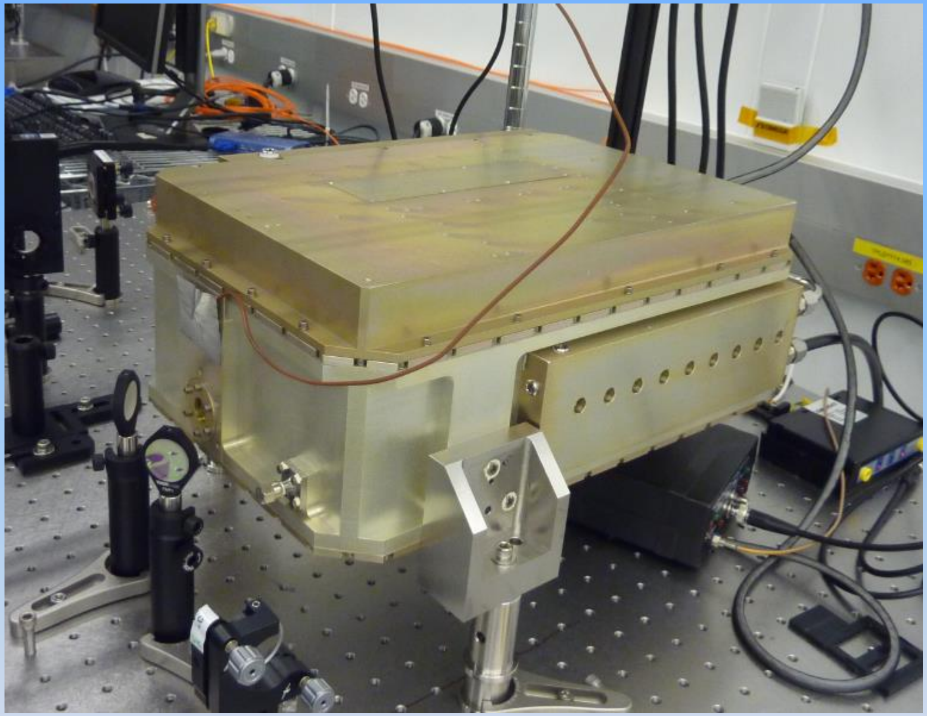


EDU-0: March 30, 2011 update
Test Time ~1750 Hrs

•-20%ΔE_p Lifetime Estimates:
•Life(-1dB)=1200 Hrs= 7.1 weeks=0.043 TShots (≤4.5% of the goal)

EDU-1: October 15, 2011 update
Test Time 800 Hrs
(Test Dates: 09/07-10/15/2011)
•-20%ΔE_p Lifetime Estimates:
•Life(-1dB)=788 Hrs= 4.7 weeks=0.028 TShots (≤3% of the goal)

EDU-2 Laser Details and differences with flight system

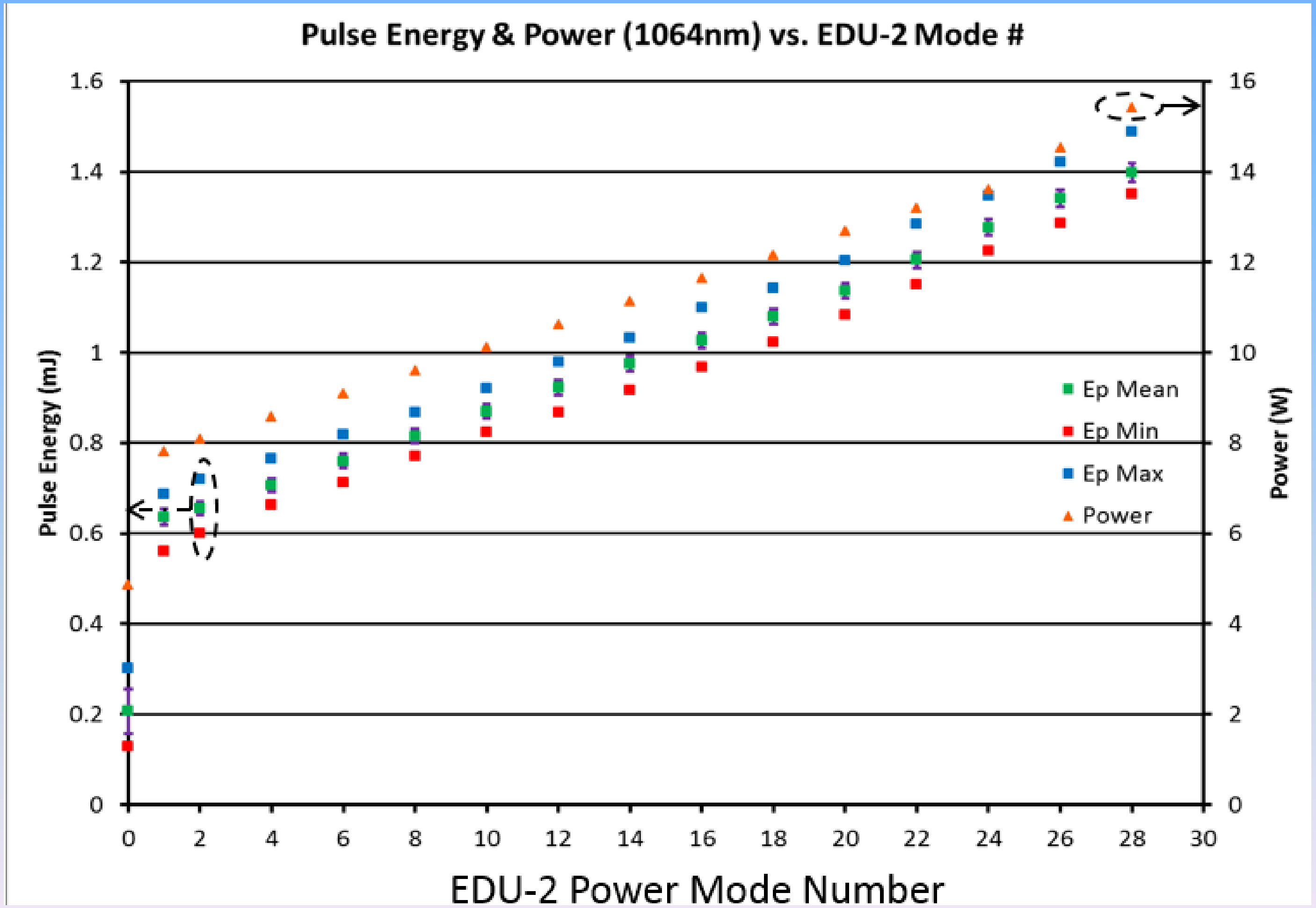


- **Frequency Doubler is Removed**
- **1-30 Power modes (1-28 declared safe)**
  - **14.5-15 W of 1064 nm max (@ Mode 28)**
  - **EDU-2 was aged @ Mode #28**
- **Older version of resonator**
  - **Non-folded**
  - **Smaller waist size**
- **Shorter VBG**
  - **Spectral width @ 1064 ~ up to 25 pm**
- **Some non-optimized mode-adjustment (1st and 2nd stage pumping varied to scan all modes)**

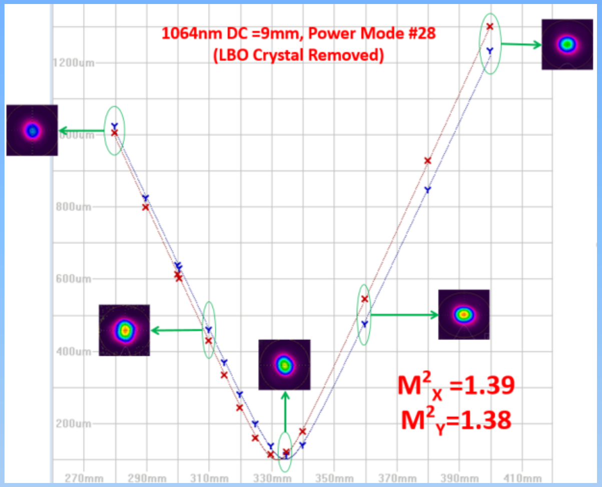
EDU-2 References:

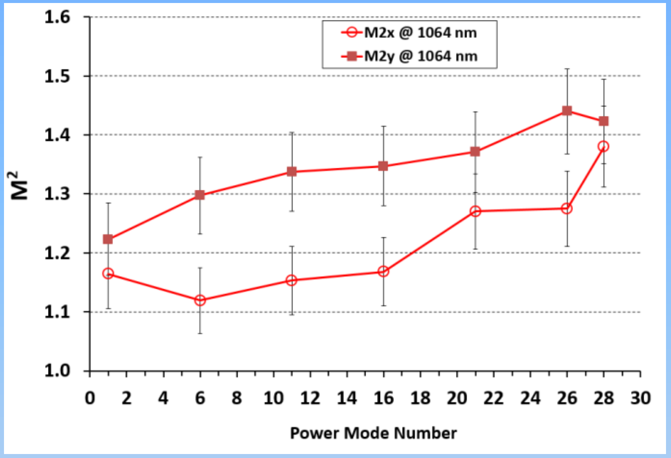
1. R. Edwards, et al., "ICESat-2 laser technology developmentProc. of SPIE Vol. 8872 (SPIE, Bellingham, WA 2013).
2. N.Sawruk, et al., "Space qualified laser transmitter for NASA's ICESat-2 mission Proc. of SPIE Vol. 8599 (SPIE, Bellingham, WA 2013)

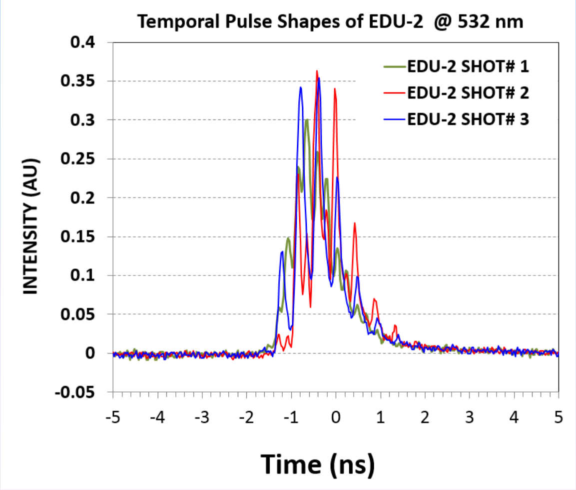
EDU-2 Output Power and Pulse Energy Measurements @ 1064nm

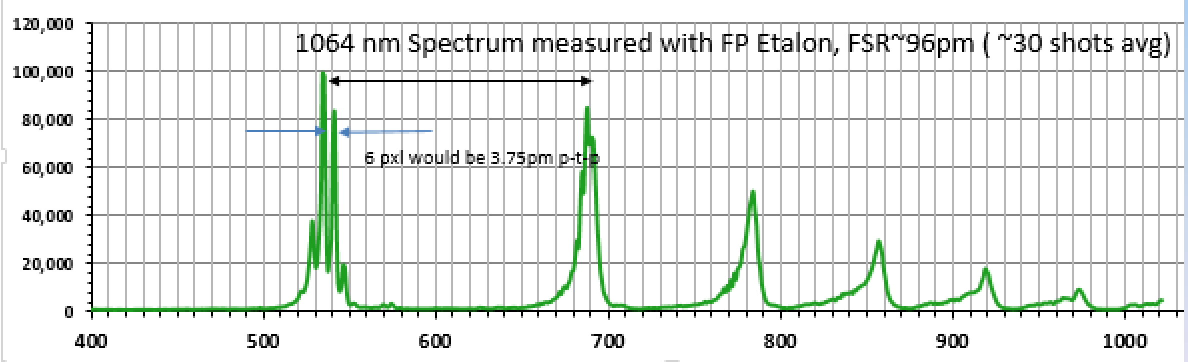


EDU-2 Typical Spatial, Temporal and Spectral Parameters at 1064 nm







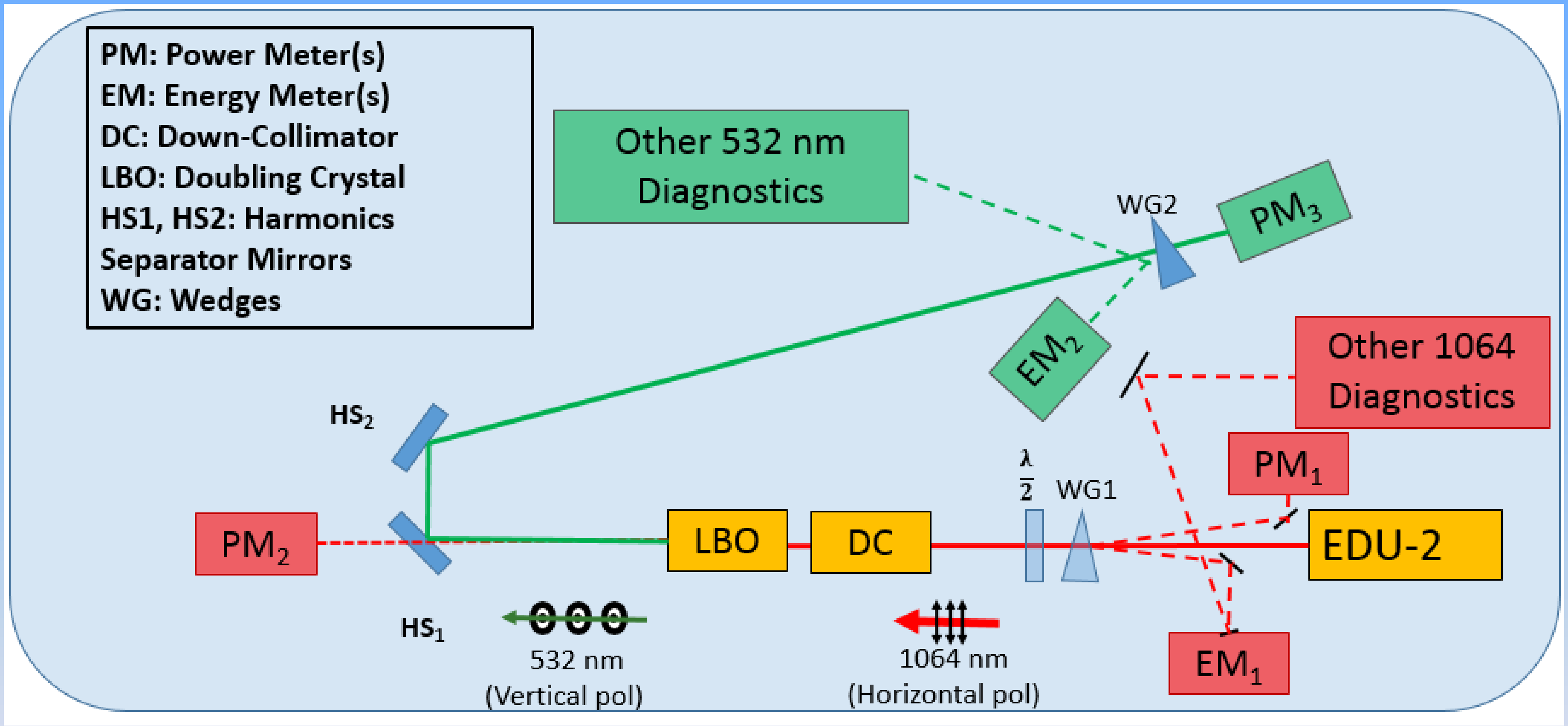


SHG Energy/Power Budget Estimates @ start of Experiment

			Assumptions: Add Coated wedge for 1064 nm Diagnostics , remove Pol cube, Add down-collimator to optimize 1064 nm beam size and SHG effciency			Optical surfaces
Item #	Parameter Description and/or Name	Dimension	Pre-Delivery Expected Values	Actually Delivered EDU-2 02/14/2012, expected values with CPM LBO crystal	Actually Delivered EDU-2 02/14/2012, measured values with NCPM LBO crystal	
1	Expected or Measured Ex-Laser Power, BOL (Watts)	Watts	>15.0	14.55	14.55	
2	Losses on WP +cube%	%	0%	0%	0%	0
3	Power After WP+Cube, max Transmission (Watts)	W	15.0	14.6	14.6	
4	Losses on Wedge (for 1064 nm diagnostics) %, actual numbers	%	2.65%	2.65%	2.65%	2
5	Losses on Wedge (for 1064 nm diagnostics) (Watts)	W	0.40	0.39	0.39	
6	Power After Wedge (W)	W	14.6025	14.2	14.2	
7	~~Throughput of HR 45 deg Mirrors~~	%	100.0%	100.0%	100.0%	0
8	Beam Focussing and/or DownCollimators Throughput	%	98.4%	98.4%	98.4%	4
9	Throughput HWP1064 (pol adjuster to doubler)	%	99.3%	99.3%	99.3%	2
10	Diffraction and Scattering losses	%	1%	1%	1%	
11	Power delivered to Doubler	Watts	14.1	13.7	13.7	
12	Estimate on SHG Efficiency (CPM based on PDR Fibertek, NCPM- based on NASA Tests)	%	65% {up to 70%}	65%	68%	
13	Expected Average SHG power ex-LBO @ 532 nm	Watts	9.2	8.9	9.316	
14	Expected Energy per pulse @ 10kHz, ex-LBO (uJ), BOL, in house test doubler	uJ	918 {up to 987}	891	932	
14a	Mission Goal (Pulse Energy)	uJ	900	900	900	
14b	Estimated BOL Pulse Energy Margin for SHG (above mission goal)	%	2.0%	-1.1%	3.5%	
15	Fundamental Power/Energy Throughput before beam reaches the first doubler surface	%	94.2%	94.2%	94.2%	
16	Fundamental Power/Energy Losses before beam reaches first doubler surface	%	5.8%	5.8%	5.8%	
	Critical Numbers in Red					

The EDU-2 laser was delivered with slightly less power (~ 0.5W less) than what is needed for both SHG up to flight specs and comfortable amount of energy for 1064 nm diagnostics

Experimental Setup Schematics

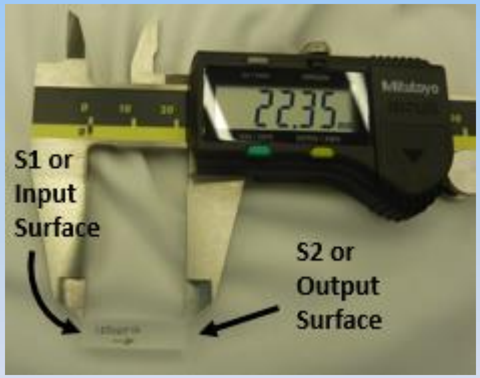


The setup consisted of two set of diagnostics of the laser system outputs, before and after frequency doubling, at 1064 nm and 532 nm. The other diagnostics include spectral, spatial and temporal measurements parameters of the beam.

Doubling Crystal Details

Information about Crystal

- LBO is manufactured by Coherent Advanced Crystal Group, Procured through Fibertek
- Dimensions
  – 6 mm x 6 mm x 22.3 mm
- Cut: Non-critical
- Phase-Matched Operation (Type-I), Non-critical
  – T_op_NCPM ~ 149 C
- Coating AR/AR 1064nm /532 nm

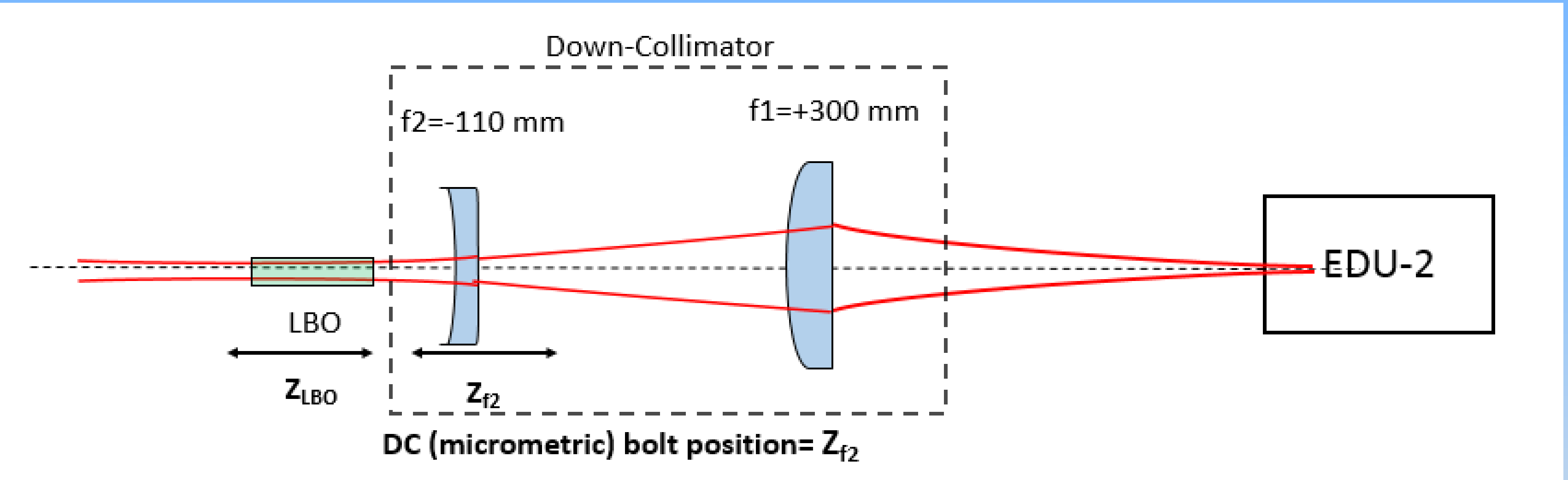


Rationale for choosing NCPM versus CPM crystal for doubler aging with EDU-2

- **NCPM-cut crystal was chosen as frequency doubler:**
  - **Due to insufficient power and pulse energy @ 1064 nm BOL**
  - **Due to no {immediate} automatic temperature tuning scanner/maximizer availability (needed due to 1064 nm beam pointing drift)**
  - **At the time of the test start, Fibertek team was not 100% sure whether they use CPM or non-CPM crystal. Fibertek has purchased and sampled both crystal cuts from the vendor and gave both LBO samples to NASA.**
  - **CPM crystal would not allow “clean” step-stress due to walk-off and SHG reduction when beam is reduced**

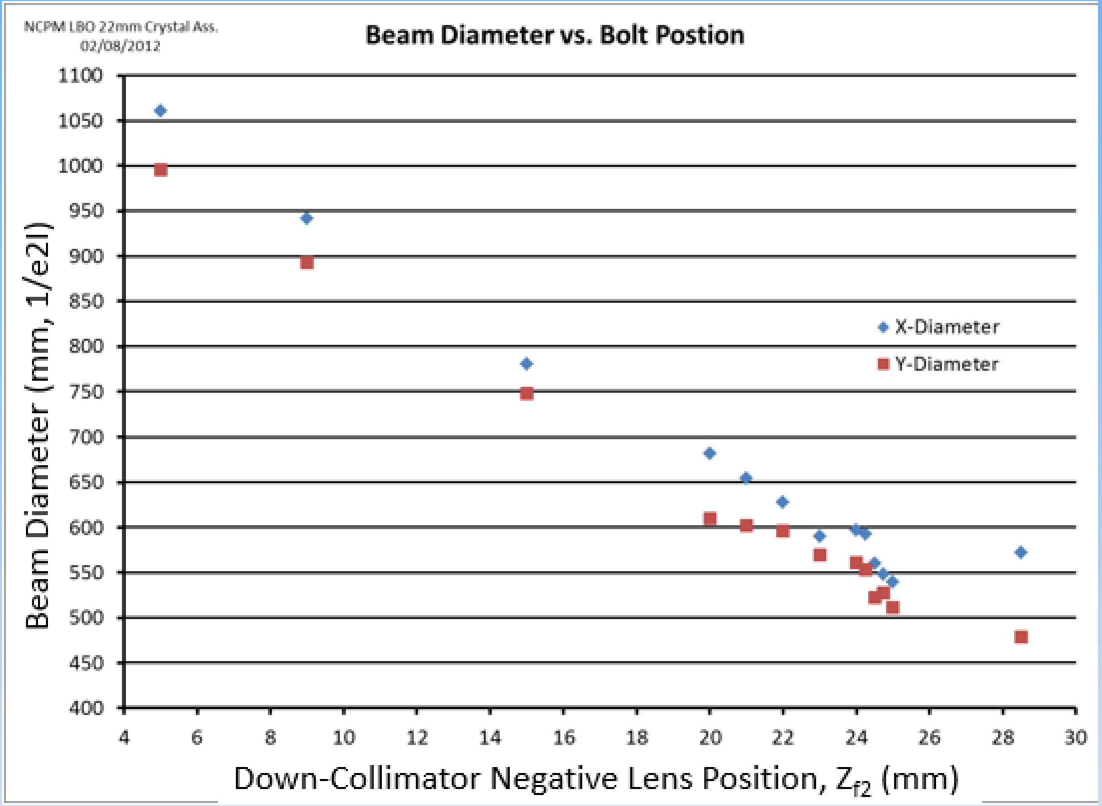
SHG Optimization and Step-Stress Choice

Down-Collimator Schematics (not to scale)



By Varying negative lens Z_{f2} - position (and by translating LBO center, Z_{LBO}, to a new waist location for each Z_{f2}) it was possible to continuously vary waist size on LBO from ~ 0.5 to 1 mm

EDU-2 Beam Waist Measurements (1064nm, Power Mode #28)

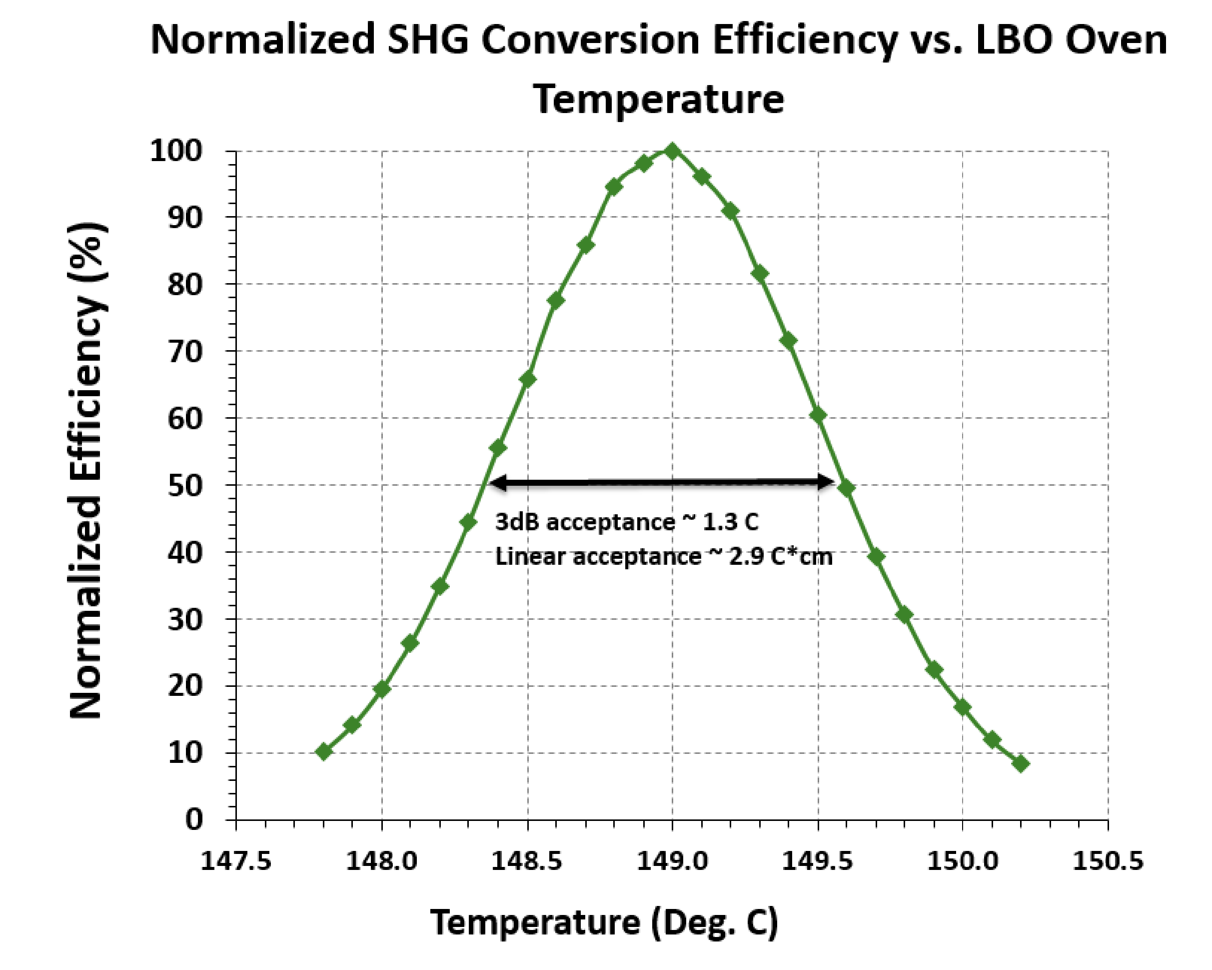


By Varying distance between down-collimator lenses, it was possible to continuously the fundamental beam diameter (*) @ 1064 nm from ~ 0.5 to 1 mm
(*) Beam Diameter (1/e2I) after down-collimator or beam size on LBO.

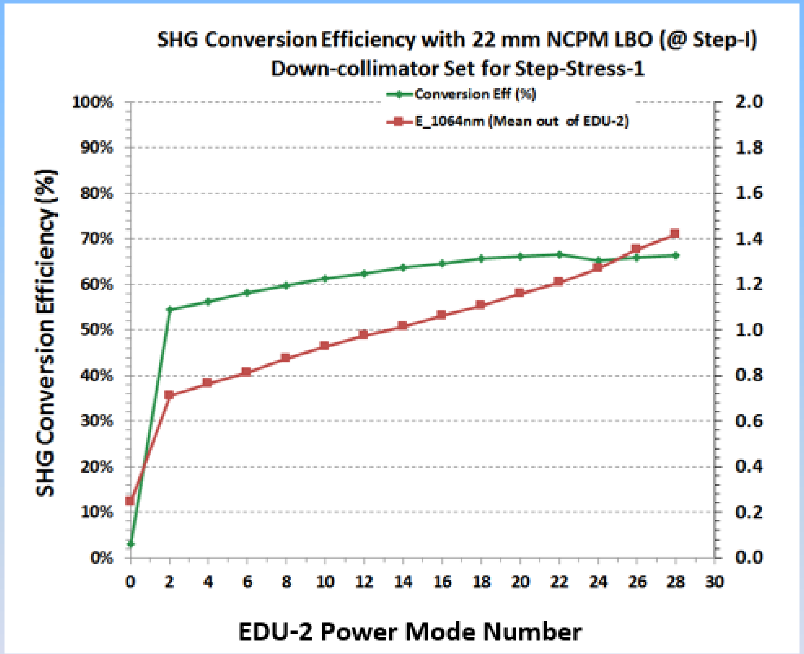
SHG Optimization steps

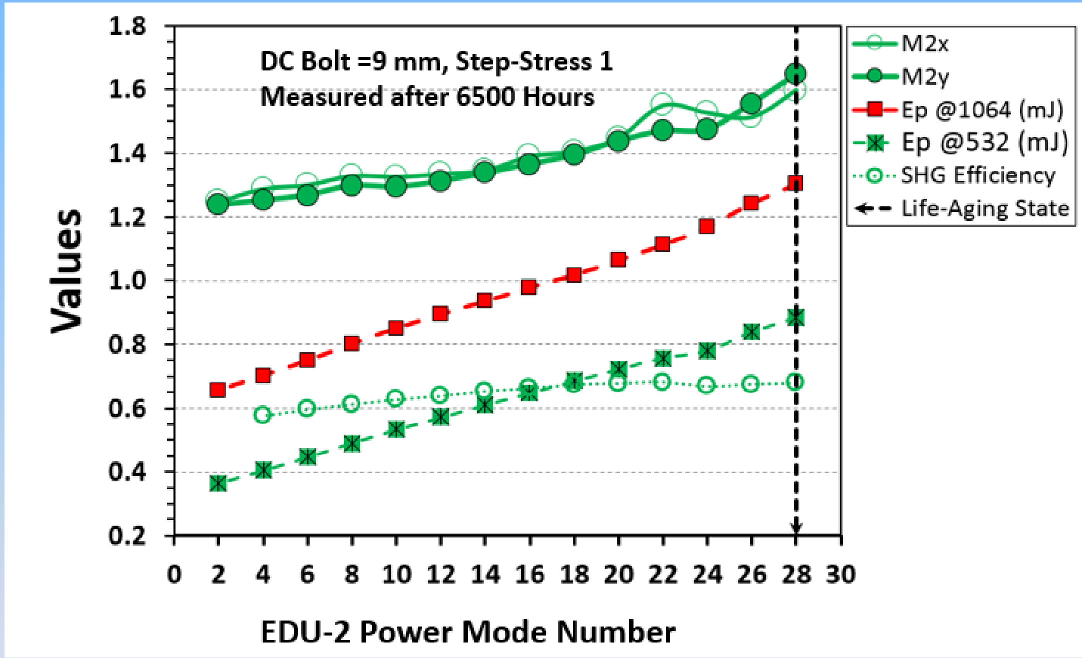
- Temperature scan
- Angular Scan
- Polarization Rotation scan
- Z-scan (M2 tests)- and adjustment of X-Y
- Spot Size Variation with Galilean down-collimator
  - And re-adjustment of LBO cell location along the beam
- Conditions: 0-1.5 mJ @ 1064 nm (up to 1.35 mJ/pulse on LBO)

SHG Thermal Optimization (peak efficiency ~ 70%)

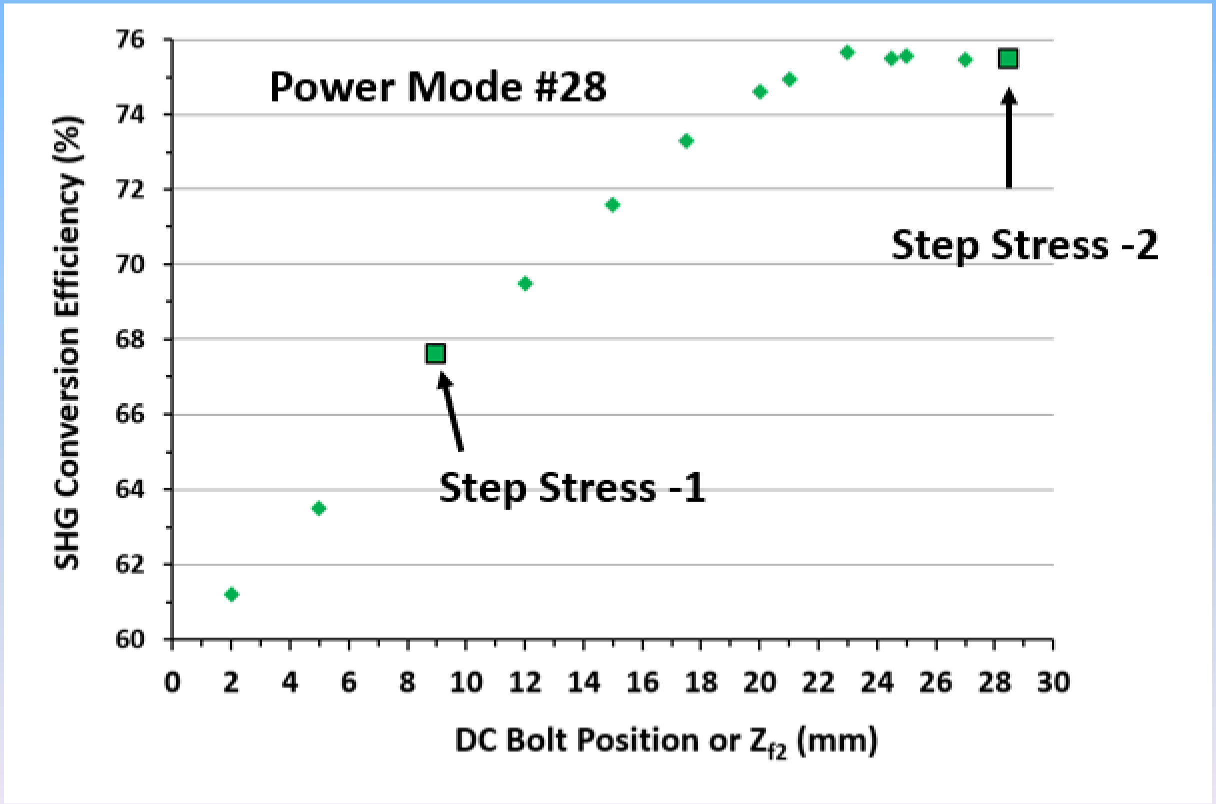


Scan of Pulse Energy, SHG Efficiency and Spatial Mode Quality (M2) versus EDU-2 Power Mode





More than 75% SHG conversion efficiency was achieved using Non-critical Phase-Matching scheme

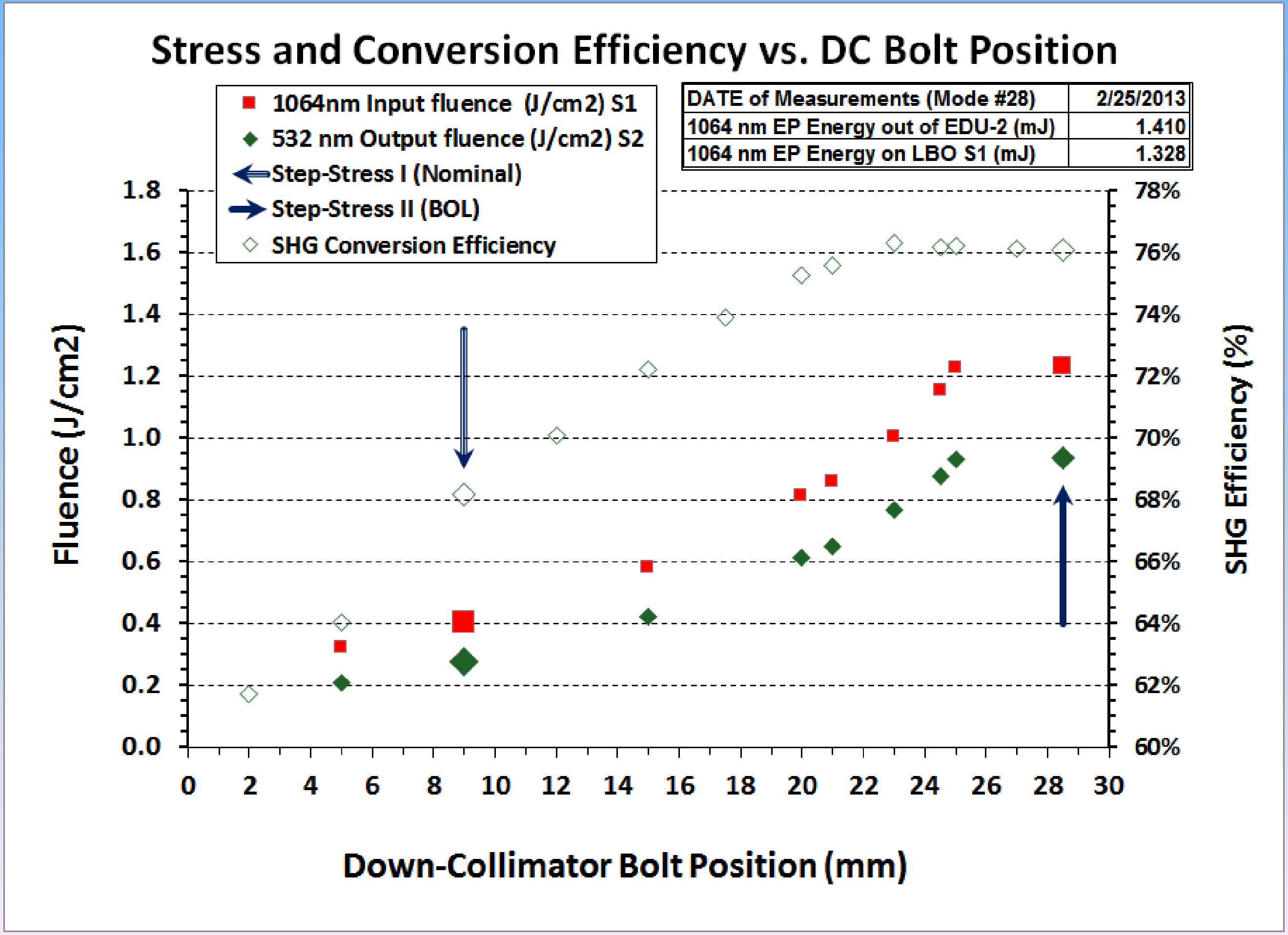


The Goal of Step-Stress-2 @ 532 nm

- After completing of close to 1 year (6,500 Hrs.) of testing doubler at nominal stress (~0.28 J/cm^2) with no measurable degradation, we increased the stress moderately to see if we can programmatically measure degradation and re-scale it to nominal conditions with an early life prediction.
- The stress at Step-2 was chosen near ≤ 1J/cm^2 {~0.93 J/cm^2}
  - This stress was chosen below that of EDU-0 (which was reported by Fibertek to be ~ 1.4 J/cm^2)
  - The chosen stress for Step-2 also allowed for the total energy on the LBO Cell to be the level required by specs since the energy supplied to the LBO Cell from EDU-2 was lower than nominal.

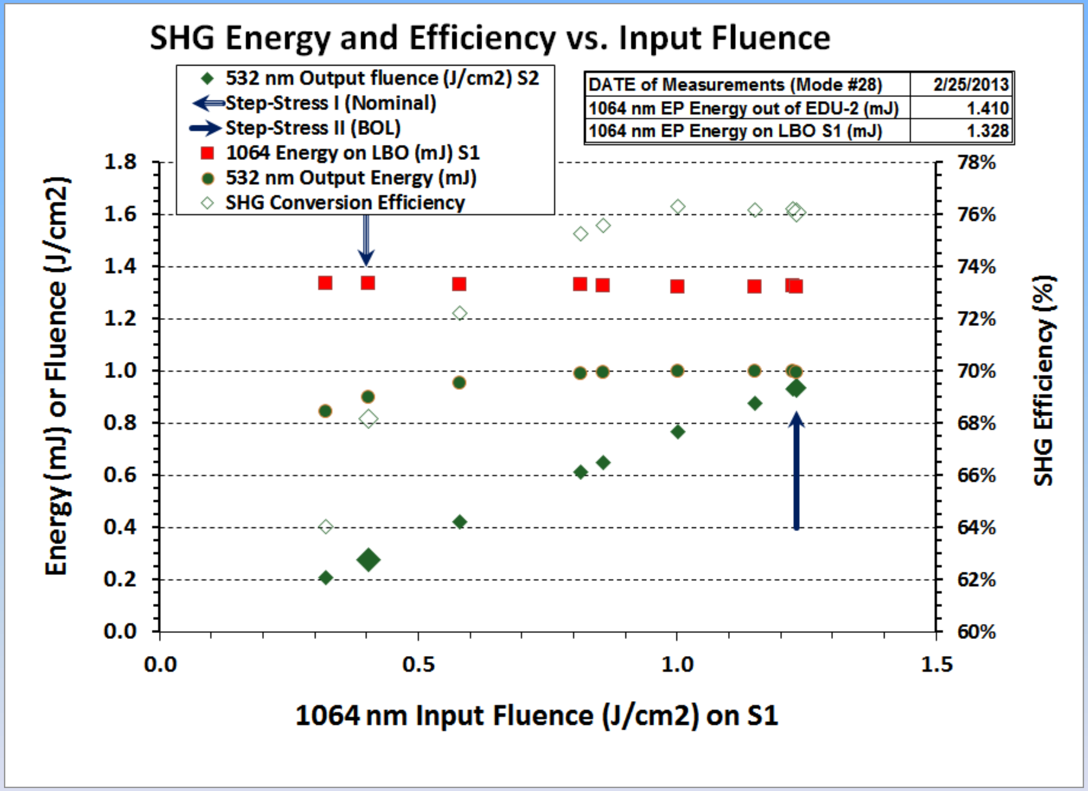
Stress and Efficiency versus Down-Collimator Settings (Lens Separation→ Waist Size)

Power Mode # 28 All Datapoints



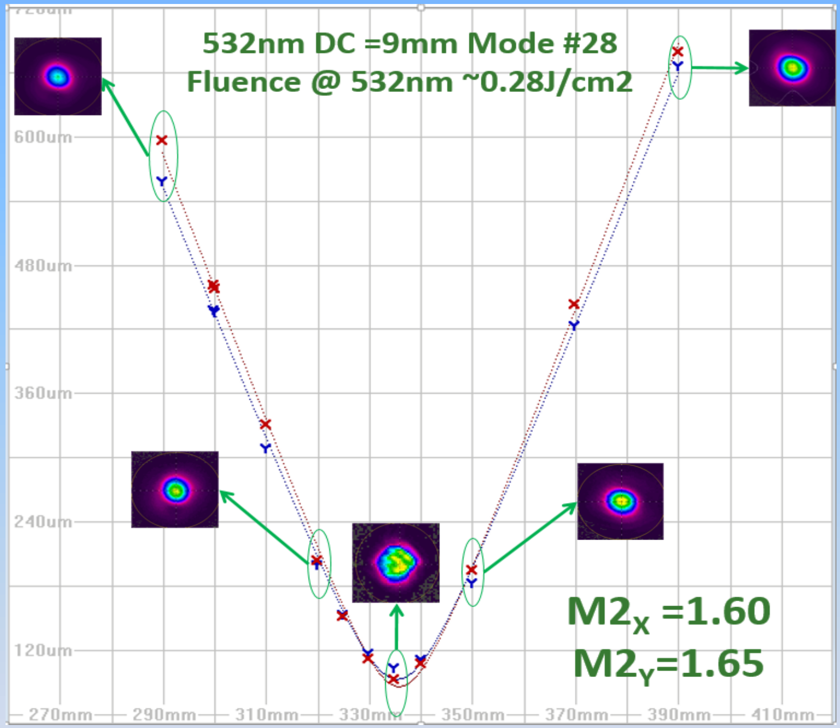
SHG Energy and Efficiency versus Input Fluence

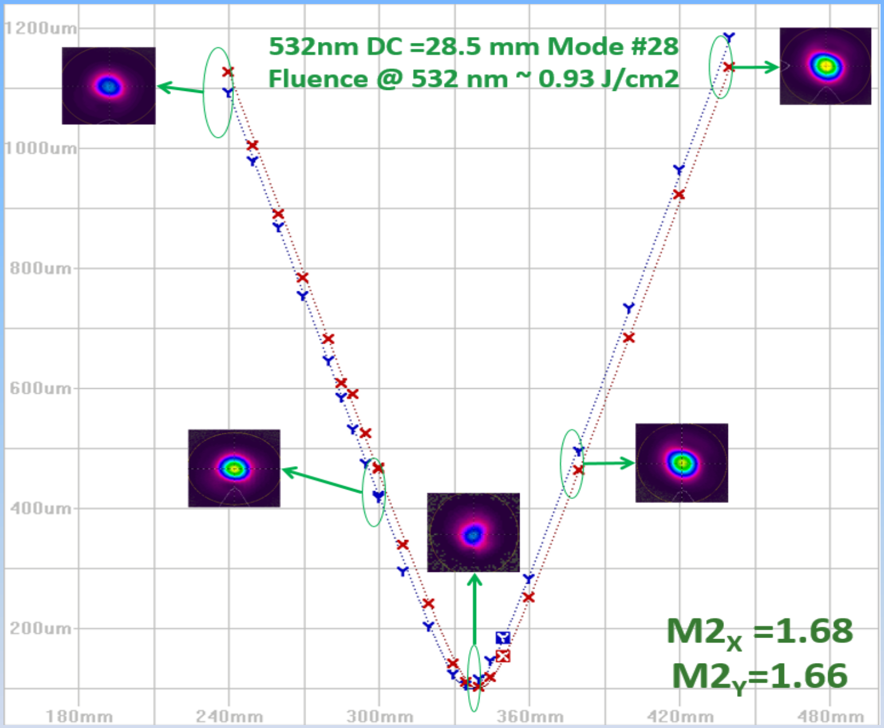
Power Mode # 28 All Datapoints



With 1.35 mJ pulse energy @ 1064 nm delivered to the doubling crystal, by varying incident fluence on the crystal, we have been able to generate between 0.8mJ and 1.0+mJ of green pulse energy. This corresponded SHG efficiency ranging from 64% to 76%.

532 nm Spatial Beam Quality



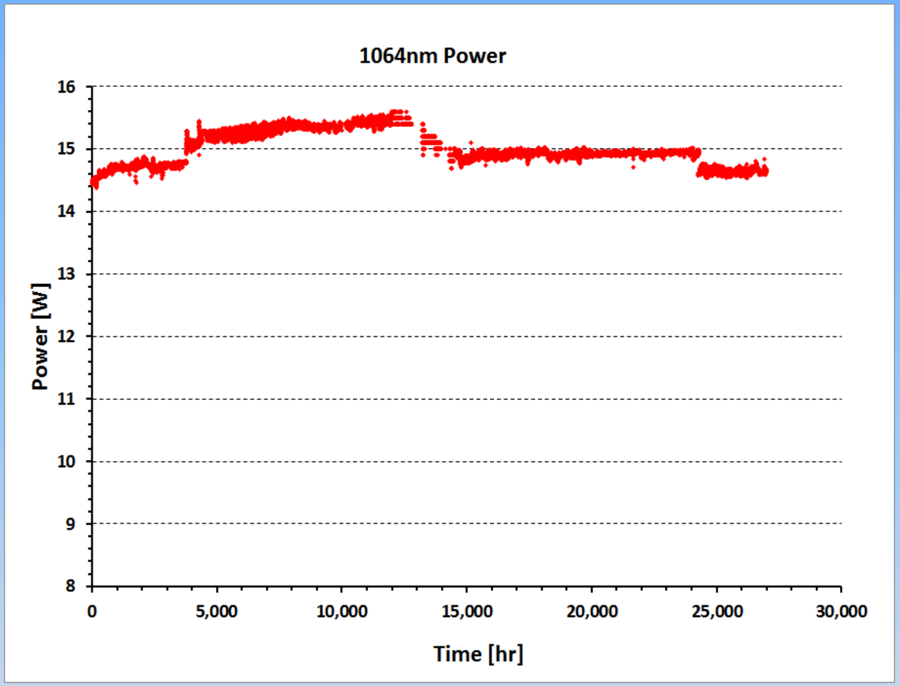


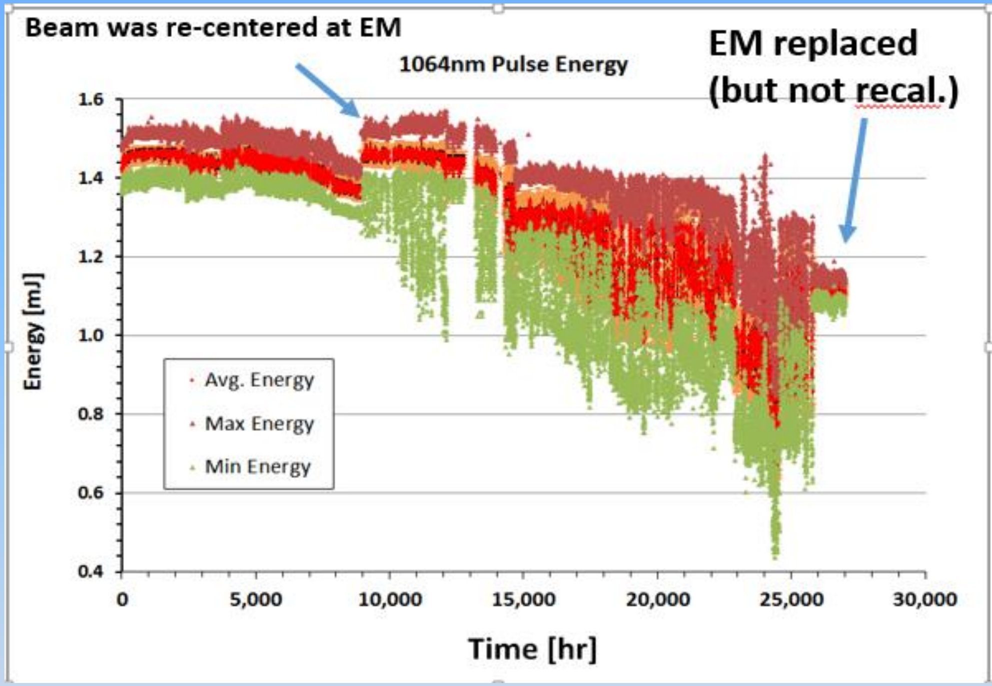
Life-Aging Timelines & Results

EDU-2 Life-Aging Timelines

- **EDU-2 Life Aging @1064 nm**
  - **3/20/2012 → 05/15/2015 (~ 26,998 Hrs. reached @ 1064 nm)**
  - **In addition, ~ 600 Hrs of burn-in was not monitored, while laser was aging.**
  - **With all time counted, aging at 1064 nm is at ~99.6% of the goal of 3yrs +2 month (=27.8 kHrs).**
- **LBO-based SHG cell was added on 5/10/2012**
  - **Step-Stress-1, Doubler Aging (Nominal Stress)**
    - **Started 5/10/2012 ; Ended 3/05/2013**
    - **Total Hours Accumulated : ~ 6,513 Hrs.**
    - **Power & Energy Degradation: ~ 0% (≤ 0.68%/KHr)**
  - **Step-Stress-2, Doubler Aging (Increased Stress)**
    - **Started 3/07/2013 ; Ended: 5/15/205**
    - **Total Hours Accumulated : ~ 18,708 Hrs.**
    - **Power & Energy Degradation: ~ 20%, linear**

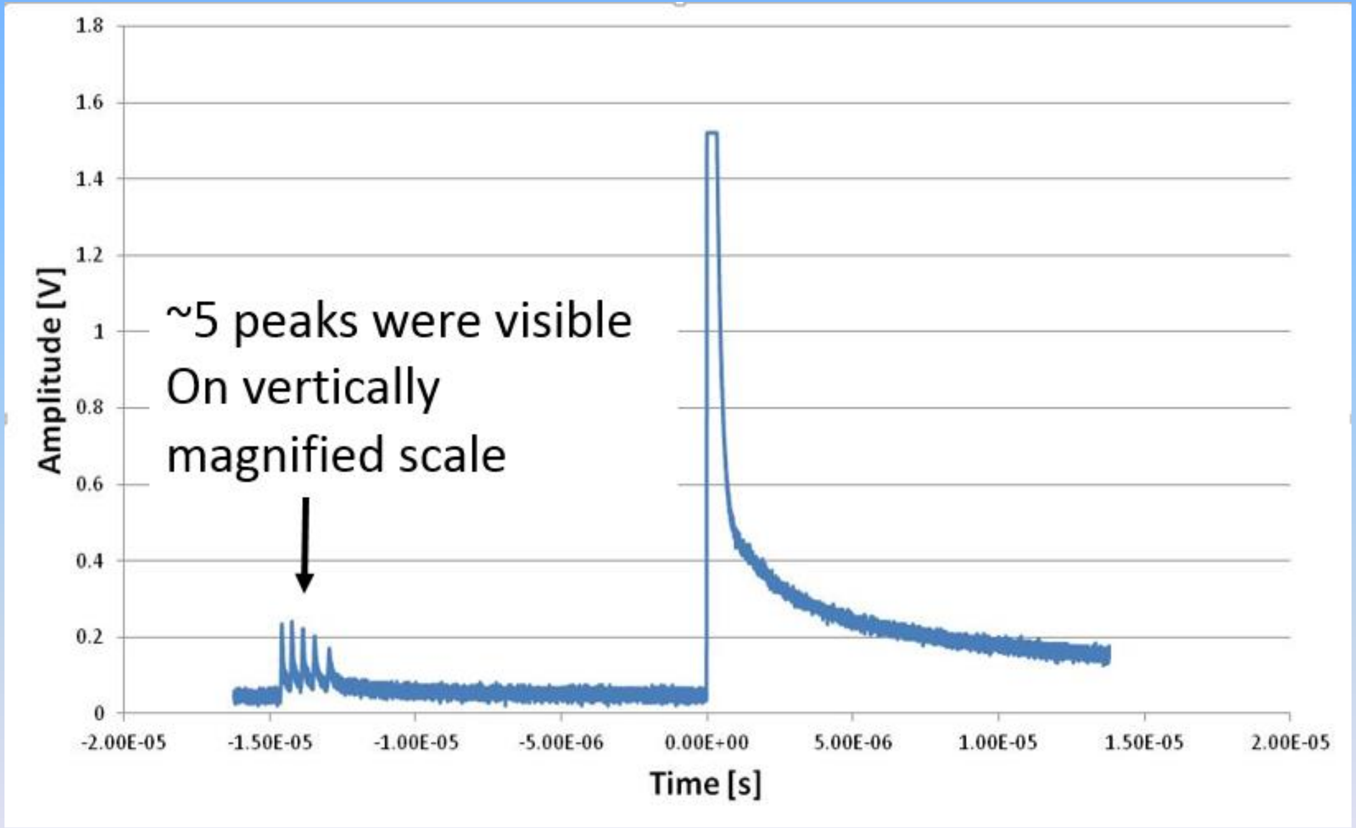
The changes and degradation of the power and energy for 1064 nm beam



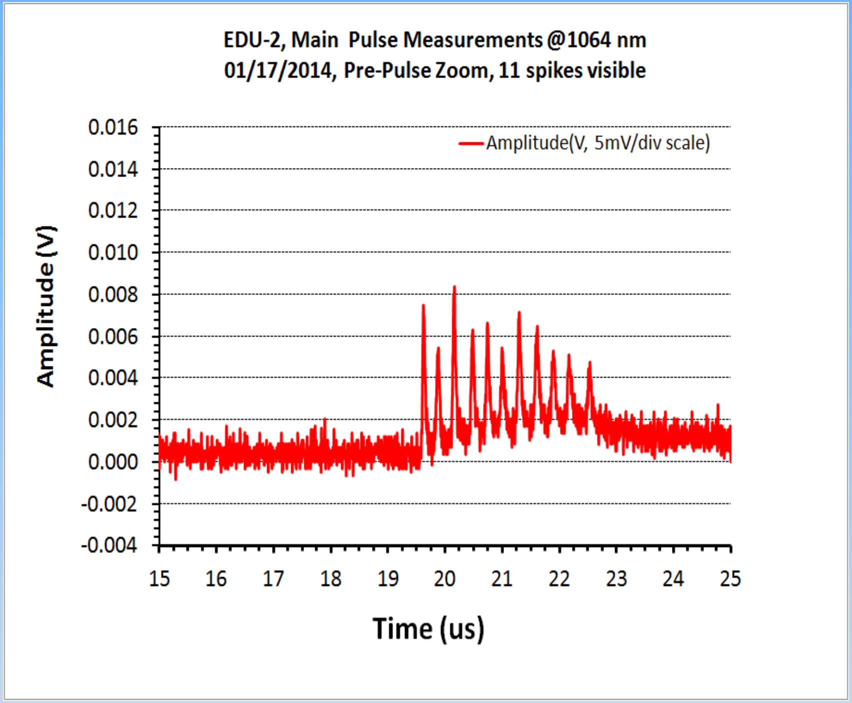


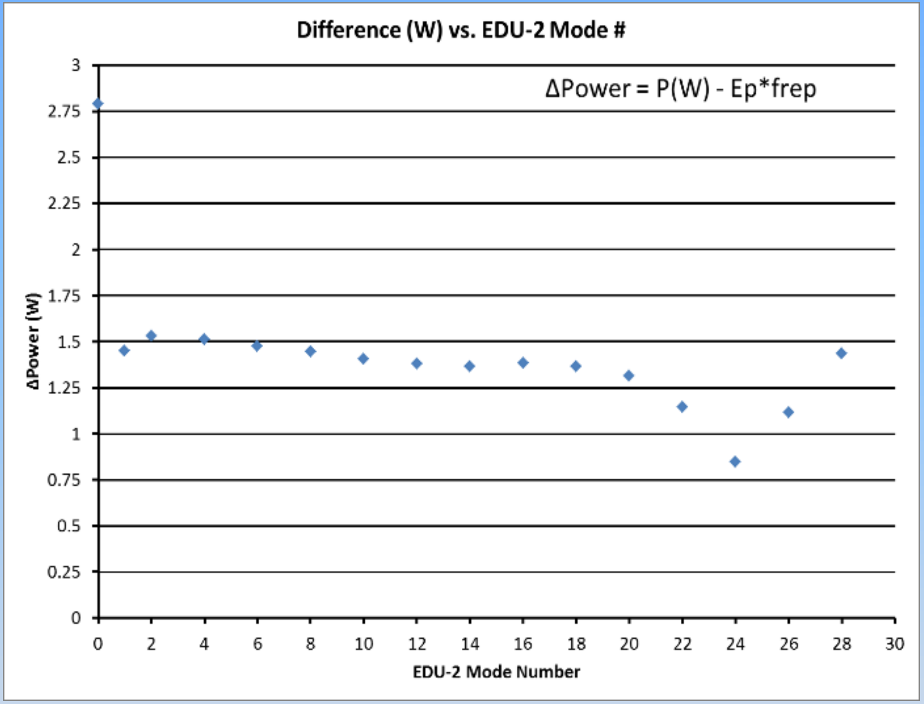
Power and Pulse Energy measurements at 1064 nm were inconsistent with each other after ~ 5,000 hrs. Fundamental pulse energy fluctuations (especially large min energy excursions after ~9.3 kHrs) were also inconsistent with those at 532 nm. The large excursions were removed when energy meter (EM) was replaced (without recalibration to the main output beam) near 26 kHrs

Measurement of Pre-Pulse @ 1064 nm after 4350 Hours



Measurement of Pre-Pulse @ 1064 nm after 16,000 Hours





Estimates Based on Scope Measurements (and waveform integration)

E_prepulse/(E_main+E_prepulse) ~ **15.2%**

Estimates Based on Power/Energy Meter Discrepancy Measurements

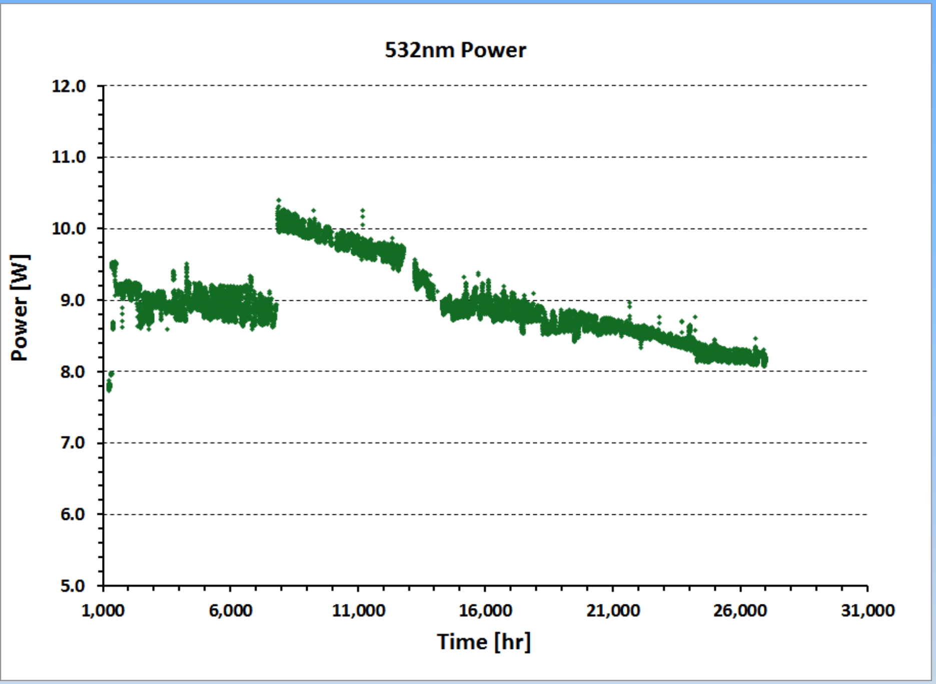
P_avg = 14.82W

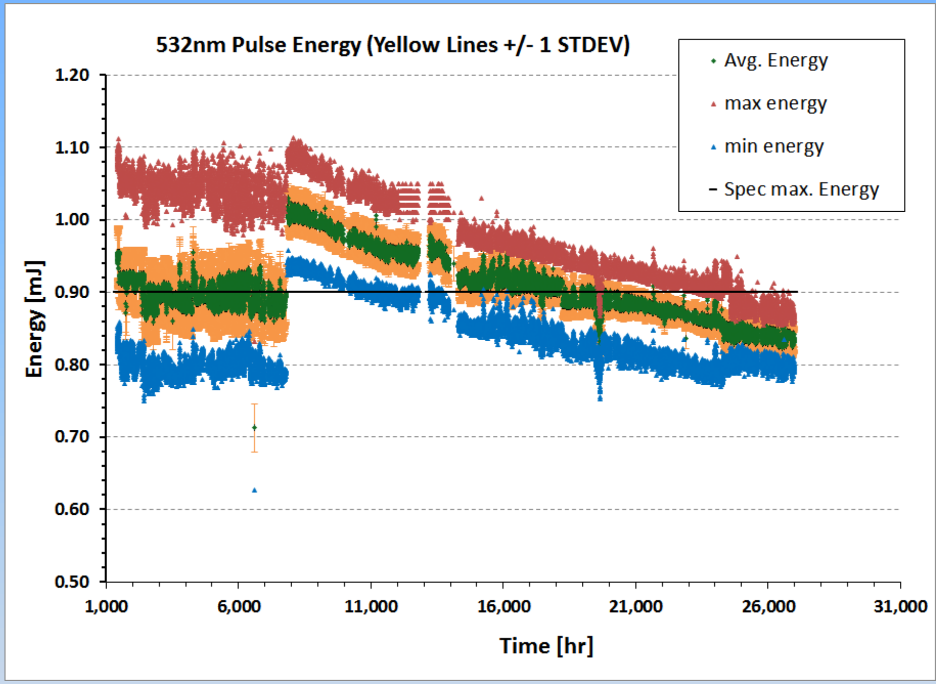
E_p =1.25 mJ (@ 10kHz)

Percentage of Energy that is not in the main pulse:

(P_avg-E_p*10)/Pavg ~ 15.65%

532 nm Power and Pulse Energy Trends (1-27 KHrs)



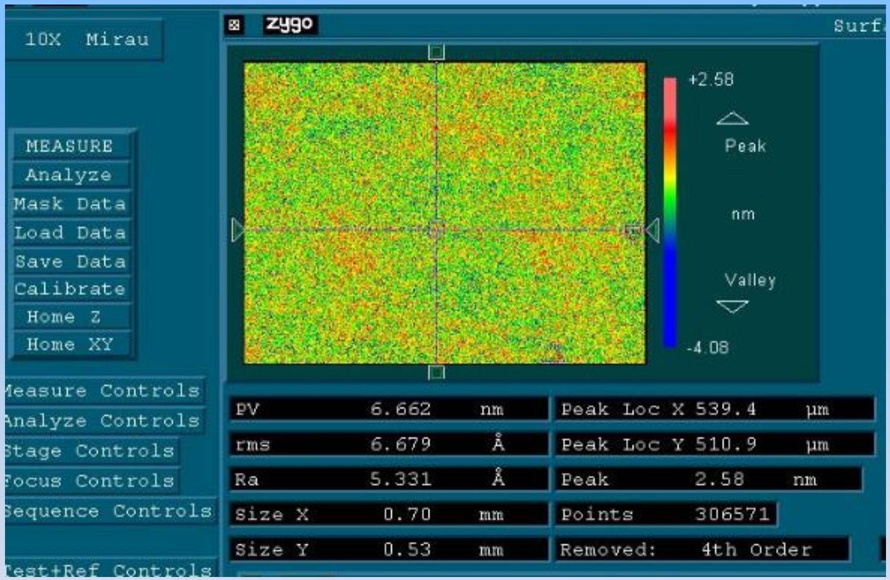


Power and Pulse Energy measurements @ 532 nm were consistent with each other. At the first step-stress, power and energy showed almost no trend, while at the second step-stress, both power and energy showed consistent downtrend

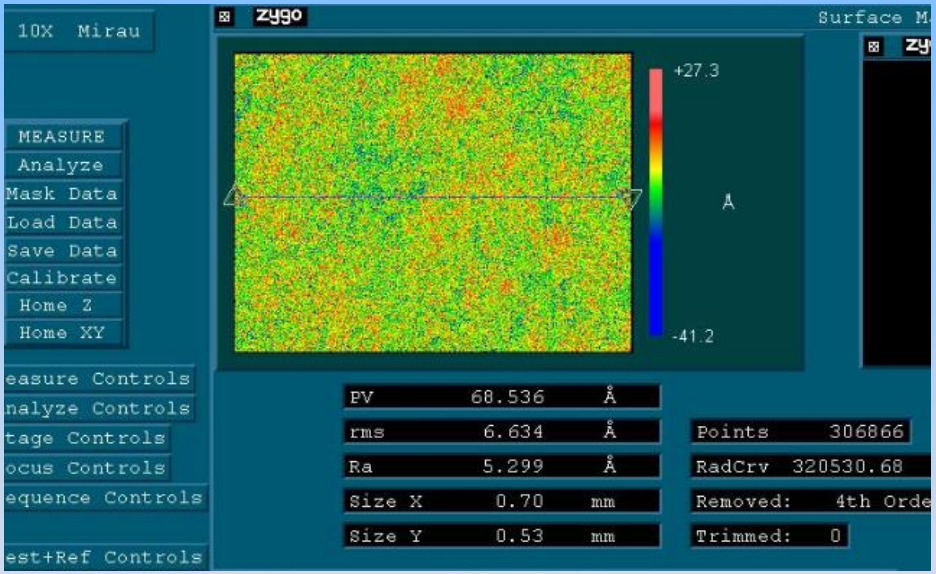
Doubling Crystal 3D Surface Profilometry

3D LBO Surface Pre-Test at Magnification =10X

Input Surface, S1, Sample, M=10X



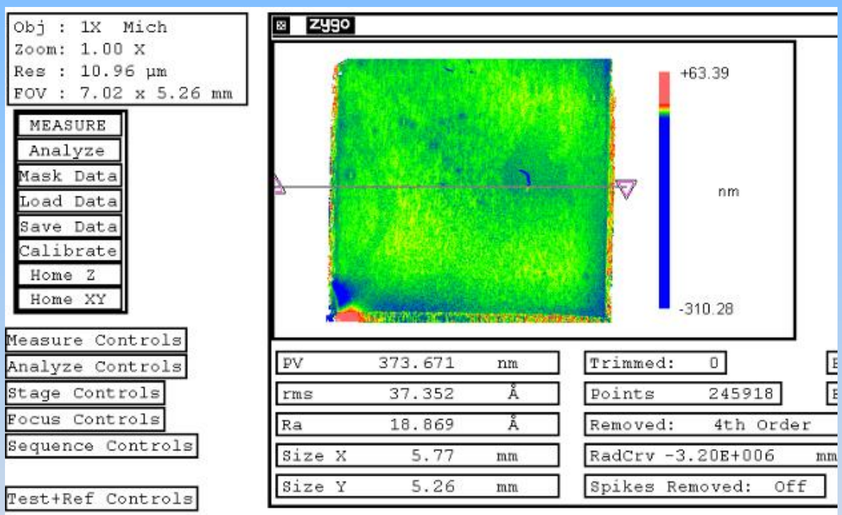
Output Surface, S1, Sample, M=10X



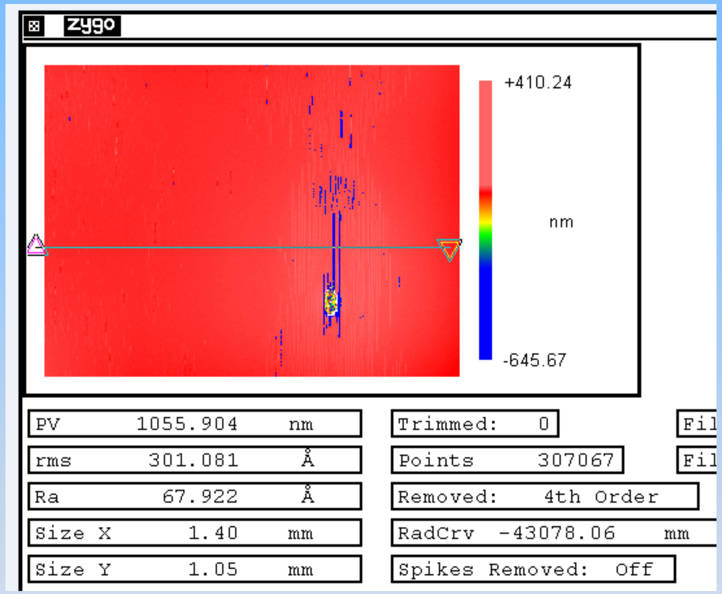
FOV =0.7X0.53 mmxmm. Lateral resolution is 1.1 um. Single interferometric scans without averaging is shown. Both surfaces had featureless profiles with r.m.s. roughness below few Angstroms. After averaging (not shown) r.m.s. roughness was below ~ 2-3 Angstroms.

LBO Surface Post Test, Low Magnification 1x (S1) and 5x (S2)

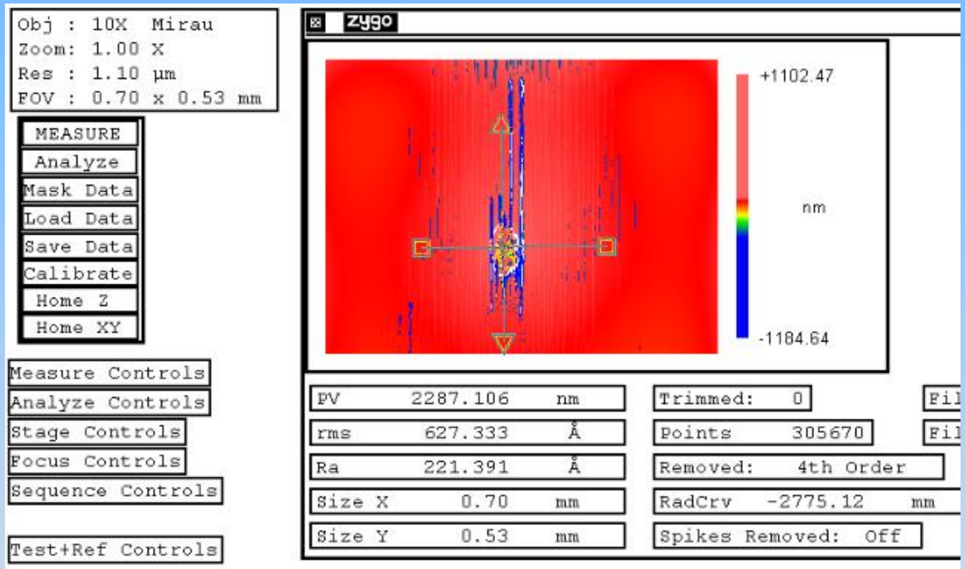
Surface 1, M=1, 6x5 mmxmm fits into screen

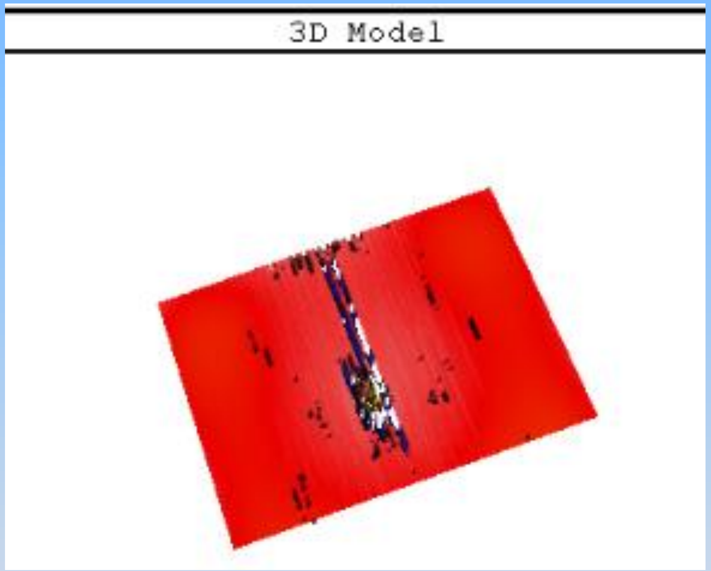


Surface 2, M=5X



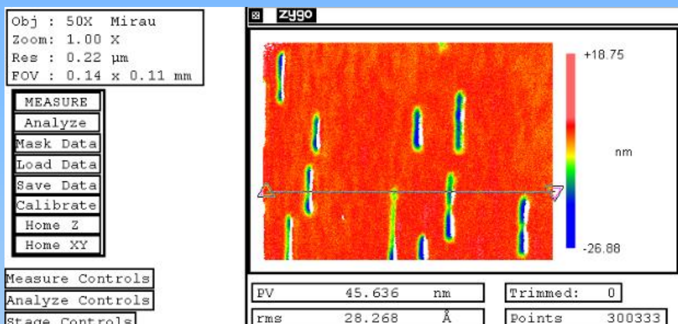
LBO Output Surface Post-Test (10x, FOV 700x530 um, Lateral Resolution ~ 1.1 um)

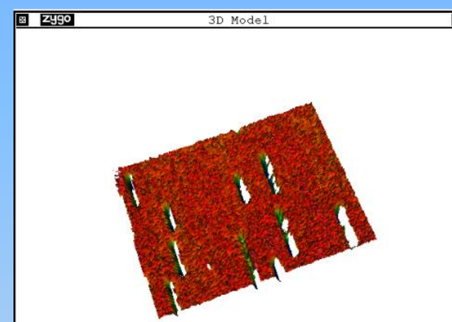


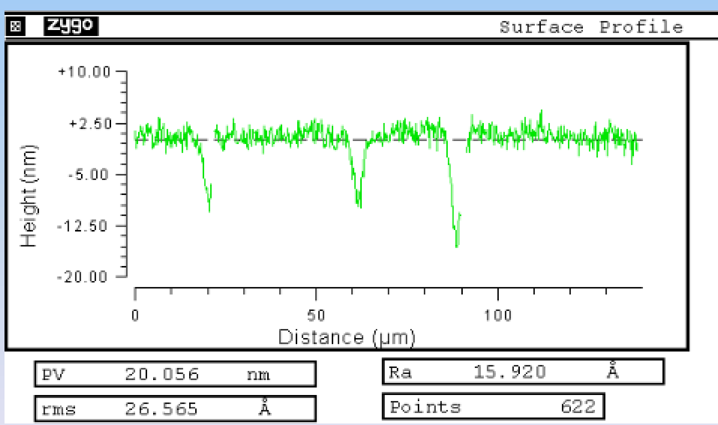


After Aging, the output surface developed a major damage site and numerous micro-cracks located all over 6x6 optical surface of the crystal

LBO Output Surface, S2, Post-Test (50x, FOV 140x110 um, Lateral Resolution ~ 0.25 um)



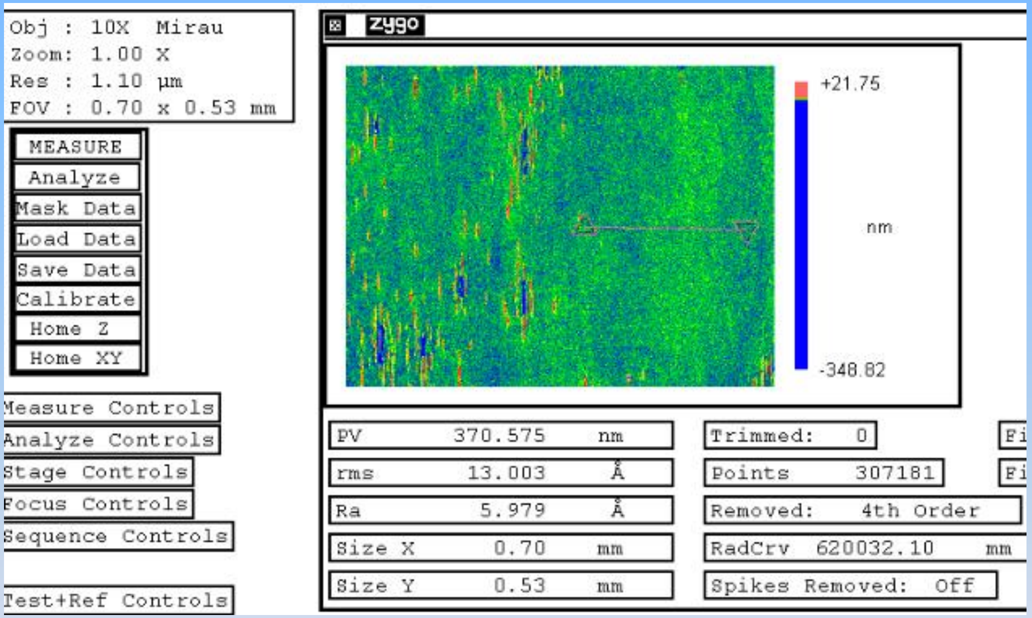


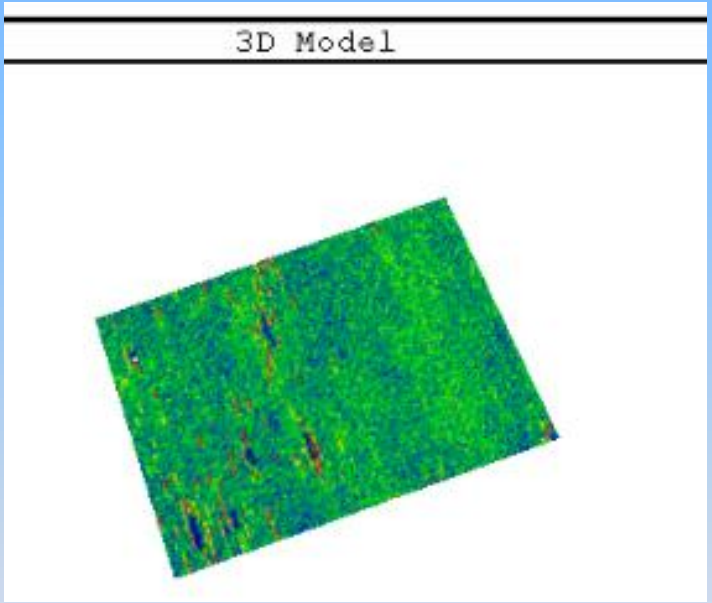


After aging, Output LBO Surface (Coating) Exhibited shallow linear & parallel surface cracks, ~ 20-50 um long, ~ 5-10 um wide and 10-20 nm deep.

There are micro-cracks located outside the incidence of the main beam

LBO Off-Center Output Surface, S2, Post-Test (10x, FOV 700x530 um, Lateral Resolution ~ 1.1 um)





Off-center-incidence S2 3D surface profiling revealed micro-cracks. These micro-cracks had much smaller density. Some surface areas had no cracks at all.

Lifetime Predictions (based on degradation of frequency Doubler)

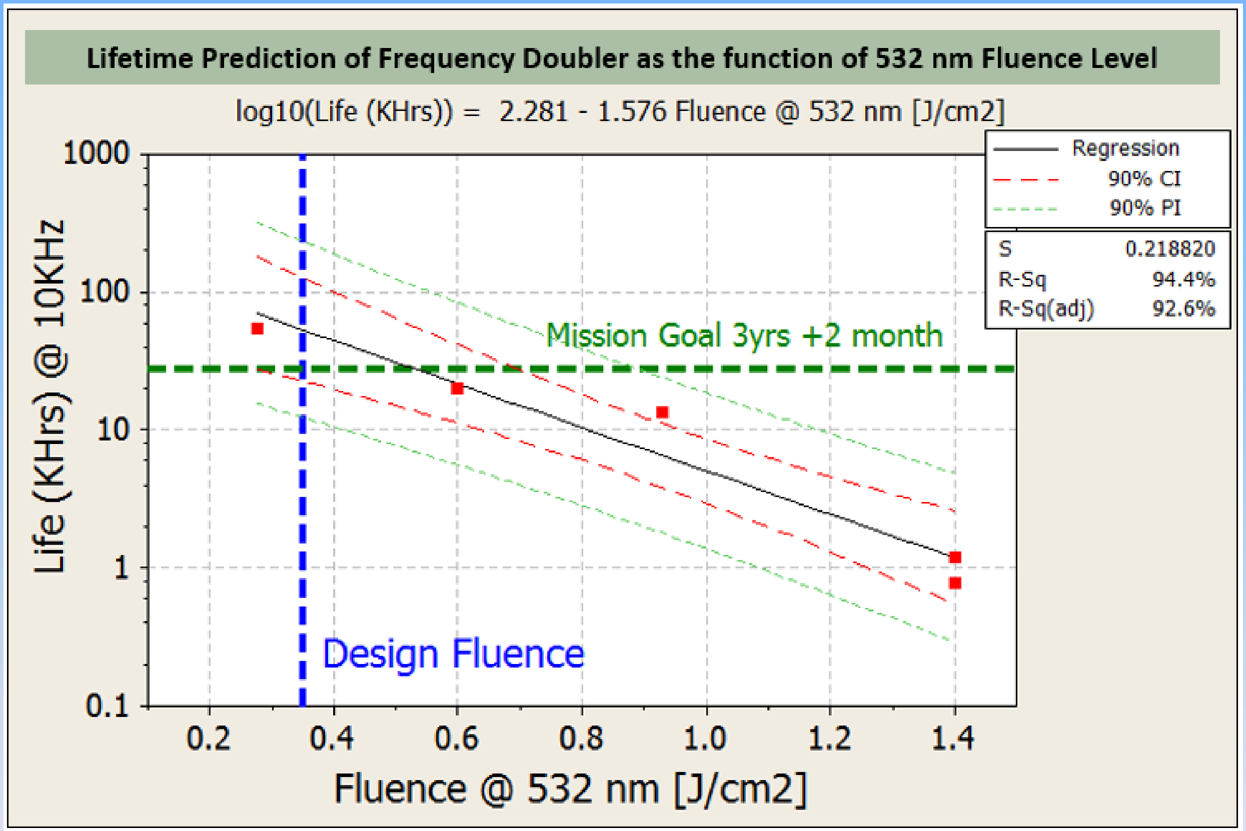
Similarity and Differences of various life-tested laser system within ICESAT-2 project

Major Difference Parameter	ATLAS/ICESAT-2 laser Operating in Space (Base)	Life-Test Laser	EDU-2 with External Doubler	MOPA BB 1	Consequences for lifetime
Intensity/Fluence Level 532 nm on LBO	<= 0.3-0.35 J/cm^2, highest power mode	The same	The same in Step Stress 1, higher at Step-Stress 2	Slightly higher than flight laser	**If surface degradation (accumulation of increased absorption, darkening of exposed surface) is the main mechanism of reduction of SHG efficiency only then the fluence stress can be considered as scaling parameter for lifetime.**
Temperature of Crystal and phase-matching type	~ mid-40C, critical matching	The same	Significantly Higher, 149C, non-critical phase matching (NCPM)	The same	**In the case of higher temperature (NCPM), the growth of the bump(s) on LBO surface(s) were not observed. This may make the dynamic of degradation significantly different of flight system.**
Particulate and Non-Volatile Contamination	Controlled by contamination plan (assembly, coating integrity, baking, etc.)	The same	Different but low as well due to contamination control imposed in the lab	Different	**As soon as this parameter is low enough for all cases, we can take it out. This may be verifiable with witness test plates and visual inspection**
Volatile Contaminations (known for photo-assisted bump growth)	Controlled BOL, somewhat unknown parameter both for chemistry and level over life	The same	The same for 1064 nm. Different for 532 nm. The crystal exposed to open, circulating, air conditioned and humidified air in the lab	Different	**This is the highest and probably one of the most critical unknown of the ground tests and the mission.** -
Gravity	None	Present, different	Present, different	Present, different	**Any free particles can be drawn into beam or attract to the optical surface and create nucleation center(s) that in turn bring more accelerated growth of damage**

Summary of Observed Lifetimes based on 532 nm pulse energy degradation

Laser System	Fluence @ 532 nm [J/cm2]	Life (KHrs), EOL =-1dB	Notes
EDU 0 (The first Prototype)	1.4	1.2	20 mm LBO, Critical
EDU1 (The 2nd proto)	1.4	0.788	21 mm LBO, Critical
EDU2 Step-Stress 1	0.275	55 (*)	22 mm LBO Non-critical
EDU2 Step-Stress 2	0.93	13.5	22 mm LBO Non-critical
MOPA BB1 (@ 20KHz)	0.6	20	25 (?) mm LBO critical
MOPA 2		TBD	
LifeTest Laser		on-going	30 (?) mm LBO, critical
(*) Linearly Extrapolated Value. Have rather large error. Test was too short to reveal onset of photo-contamination if any.			

Life-Time Prediction of Frequency Doubler as a function of the peak fluence of 532 nm pulse



Note: The Graph include the results of the tests of the 4 items from the previous slide.

Conclusions

- The experience acquired during this three-year test of the EDU-2 laser with an external frequency doubler revealed both reliable and unreliable parameters
  - The pulse energy at 1064 nm had some degradation (but potentially restorable) that can be attributed to pre-lasing or pre-pulse build up. A low-energy pre-pulse up to 15% of total energy developed
  - The 532 nm pulse energy degradation rate critically depends on the 532 nm fluence stress and ambient conditions (volatile contaminants). Fluences < 0.3-0.5 J/cm^2 needed (<0.2J/cm^2 for high confidence level)
- For the final flight design several measures taken
  - The doubling crystal length was increased and thus fluence was decreased by 2.8 times relative to the early engineering units.
  - To control and reduce contaminant level, activated charcoal getters were added to the system to mitigate contamination risk.
- The flight-like laser system test is underway